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THE NEED FOR A CONTROLLING MIND IN SEISMIC ENGINEERING

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Abstract: *Within the wide range of engineering disciplines required to deliver a typical infrastructure project, seismic engineering is considered a specialism. Within this discipline, there is a range of sub-disciplines which may be required to deliver a major project. The sub-disciplinary practitioners include geologists, seismologists, geophysicists and geotechnical, structural, mechanical and electrical engineers. In recent years, the boundaries between these sub-disciplines have become more distinct, perhaps reflecting an increase in knowledge and computational ability.*

The contribution of each sub-discipline, as well as the relationship between seismic engineering and other professional disciplines, needs to be managed and controlled in such a way that the project is designed and constructed as a coherent whole, to provide a safe, efficient engineering solution. Questions emerge; how do you keep control of this process? How do you ensure that these sub-disciplines work as a coherent whole, such that the uncertainty, risk and conservatism inherent in the process are addressed in an appropriate manner?

In this paper, the need for a 'controlling mind' in seismic engineering projects is proffered as an essential ingredient in obtaining a safe, efficient engineering solution. Several examples are presented, illustrating the necessity for strong interface management and exploring the consequences of what can happen when good project protocols are absent. If the design substantiation is to be robust, there must be internal consistency in the data, design assumptions and the treatment of uncertainty at all stages of the process, from the seismic hazard assessment, through the geotechnical and structural engineering, to the design of plant, equipment and building services.

With the increase in specialist skills within seismic engineering, there is increasing need for the 'seismic generalist' who can provide oversight of an entire project and perform the role of the controlling mind.

Introduction

Seismic engineering is, by its nature, complex. The initiating event, an earthquake, is a highly non-linear perturbation which invariably invokes a non-linear response in the ground, structures and plant which form the infrastructure on which humanity is reliant. When considered across the full spectrum of the design process, it involves many disciplines, from geology and seismology, through geotechnical, civil and structural engineering to mechanical and electrical engineering, and many other disciplines in between. Few people possess knowledge of all of those disciplines, yet such knowledge, or at least a good understanding of those disciplines is required to deliver infrastructure that will withstand seismic events in a safe and efficient way.

This paper examines the relationships between the various disciplines involved in the delivery of seismically engineered infrastructure and illustrates by way of example, some of the issues that can arise. The skills required to manage the delivery of seismically engineered infrastructure are also examined.

In seismically active areas of the world, designing structures to resist the effects of earthquakes is a common occurrence, i.e. it is a standard part of the design process, albeit the application and enforcement of design standards can be mixed. In low seismicity areas, like the UK, designing structures to resist the effect of earthquakes is usually the preserve of high hazard industries like the nuclear industry, where the consequences of failure could be significant for large areas of habitation.

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High hazard industries are, without exception, subject to statutory controls in the form of legislation and regulation. This in turn yields a body of guidance documents, a thorough approach to work, and robust implementation of checking and review procedures, throughout all stages of a facility life cycle. This paper is written from the perspective of high hazard industries, particularly the nuclear industry, as practiced in the UK and overseas. Given the potential consequences of an earthquake on a nuclear facility, seismic engineering forms a significant part of the nuclear safety case, and the engineering effort required to justify the safe operation of a facility at low annual frequency of exceedance (AFoE) events can be substantial.

Guidance does not just arrive out of nowhere; it evolves over time, frequently as a result of times when things did not work or did not go as well as planned. It is therefore worth studying guidance documents before embarking on a major project. Of particular note, is the guidance issued by the International Atomic Energy Agency (IAEA), the UK Office for Nuclear Regulation (ONR), and the United States Nuclear Regulatory Commission (USNRC).

The need for experts

In a seismically engineered project, the need for specialist expertise pervades the whole delivery process from concept design through to completion, operation and ultimately decommissioning. By way of example, the IAEA capture the need for specific expertise in relation to seismic hazard assessment in their guidance document SSG-9, ‘Seismic hazards in site evaluation for nuclear installations’ (IAEA 2022):

> *“The evaluation of seismic hazards for a nuclear installation site should be done through the implementation of a specific project plan for which clear and detailed objectives are defined, and with a project organization and structure that provides for coherency and consistency in the database and a reasonable basis on which to compare results for all types of seismic hazard. This project plan should include an independent peer review. It should be carried out by a multidisciplinary team of experts, including geologists, seismologists, geophysicists, seismic hazard specialists, engineers and possibly other experts (e.g. historians) as necessary. The members of the team for the seismic hazard assessment project and the independent peer review should demonstrate expertise and experience commensurate with their role in the project.”*

The expertise captured in that statement, whilst specific, is also over-lapping; one would reasonably expect geologists, seismologists and geophysicists to have an understanding of each other’s area of work. This need for specific, yet over-lapping expertise runs through the entire project delivery process, from seismic hazard, structural design, mechanical and electrical design, to the test and commissioning of plant. It is also worthy of note, that the statement from the IAEA, refers to ‘experts’, as opposed to mere ‘specialists’; the inference being that specific expertise is required to fulfil these roles. Indeed, on many large nuclear projects, the experts employed on some tasks would be considered to be world-leading in their field.

A typical project evolves through many phases; Project Definition, Feasibility, Site Selection, Concept Design, Scheme Design, Detailed Design, Implementation Design (in the case of mechanical and electrical works), Construction, Commissioning, Operation and (ultimately) Decommissioning. Whilst the terms involved in the various stages of a project life cycle may vary, the concept is the same; information developed in one phase evolves and is developed further in later phases, often by different disciplines with different skill sets. Seismic engineering is, of course, a small, albeit important, part of a project. Considering only the design phases of a project, addressing the seismic elements is likely to involve geologists, seismologists, civil, structural, mechanical and electrical engineers, among others. The mechanical engineer designing the overhead crane will have little understanding of the seismic hazard developed by the seismologist, yet fundamentally they are addressing the same earthquake, with the same epistemic uncertainties and aiming to protect the same people and infrastructure with a consistent level of safety.

As information evolves in one stage of a project and is passed to another, it is imperative that the uncertainties, assumptions and conservatisms are understood and passed on with the data, so that internal consistency is maintained throughout the design process. Since the personnel in each stage of a project may well be different, someone has to have oversight of this process and be in control; someone needs to be the ‘controlling mind’.

Controlling mind

The concept of a ‘controlling mind’ is to be found in UK legislation relating to industrial health and safety, and environmental protection. It is a legal concept which has its origins in case law relating to manslaughter. In general terms, it is understood as the concept of whether the actions of an individual equate to the controlling mind of the company such that the individual should take on the liabilities of the company.

Reference is frequently made to the judgment of Lord Denning LJ in H L Bolton (Engineering) Co. Ltd v T J Graham & Sons Ltd, (1957), 1 QB 159. He said;

> *“A company may in many ways be likened to a human body. It has a brain and nerve centre which controls what it does. It also has hands which hold the tools and act in accordance with directions from the centre. Some of the people in the company are mere servants and agents who are nothing more than hands to do the work and cannot be said to represent the mind or will. Others are directors and managers who represent the directing mind and will of the company, and control what it does. The state of mind of these managers is the state of mind of the company and is treated by the law as such.”*

The somewhat negative connotation, relating to corporate manslaughter, can be turned on its head to take a more positive view; that of the mindset which controls and influences an organisation or a project. In terms of project execution, it is the mind that sets the direction of the project, determines the approach and ensures due diligence is applied throughout the project execution to ensure the right outcomes are achieved.

In practice, the controlling mind of a project will be someone in a technical leadership position. Whilst the role and title will vary from organisation to organisation, this would typically be the Engineering Manager, or equivalent. On large projects the Engineering Manager may have a series of deputies leading individual disciplines or areas, but the Engineering Manager will remain the controlling mind.

Conservatism and the need for internal consistency

Uncertainty in the hazard and design process

Uncertainty pervades the entire process of seismic design, from the assessment of the hazard through to the construction of the facility. If the substantiation of the design is to be meaningful, the quantification of the uncertainty has to be consistent throughout the process. Ultimately, this uncertainty will be addressed by a factor of safety, or conservatism, in the design of the facility.

The ONR Safety Assessment Principles (SAPs) (ONR 2020) specifically address the issue of uncertainty. With respect to the management of safety and decision making, the SAPs (para 72) state;

> *“Decisions at all levels affecting safety should also cater for the potential for error, uncertainty and the unexpected, and those taken in the face of uncertainty or the unexpected should be appropriately and demonstrably conservative.”*

and with respect to external hazards, the SAPs (para 239) state;

> *“For external hazards, the design basis event should be derived conservatively to take account of data and model uncertainties.”*

Whilst there is a requirement for the design basis to be derived conservatively, current relevant good practice (RGP) suggests that the hazard should be derived on a best estimate basis. The objective of a probabilistic seismic hazard analysis (PSHA) is to capture the centre, body, and range (CBR) of technically defensible interpretations (TDI) (USNRC 2018). In this context the centre is the best estimate of the resulting interpretations, the body describes the shape of the distribution about the best estimate, and the range encapsulates the upper and lower limits of the TDI. By this approach, the best estimate of the hazard is captured by the preferred interpretation, and the uncertainty quantified through a logic tree formulation.

Whilst the aspiration may be to define a best estimate of the hazard, with the uncertainty captured in the fractiles of the probabilistic results, it is, of course, a moot point, as to whether one can actually define a true best estimate of the hazard, particularly for a site-specific study. The inevitable gaps in the hazard database ensure that the simplistic concept of making an objective assessment, i.e. one with no subjectivity, is impossible to achieve as there is no scientific evidence. It is of course also necessary to ensure that hazard estimates are secure against the arrival of new information. In this respect, and acknowledging the need for conservatism, it is not possible to avoid decisions which appear cautious.

Estimates of hazard exposure have to allow formally for both epistemic uncertainty and aleatoric variability and are, thus, intended (and expected) to remain stable against the arrival of all but the most extreme new data.

Design Basis

If relevant good practice (RGP) is for the seismic hazard to be derived on a best estimate basis, then the necessary conservatism must be expressed in the definition of the seismic design basis. Notwithstanding the ability, or otherwise, to define an unbiased best estimate of the hazard, it is not possible, certainly not feasible, to define a suitable design basis *a priori*. To define the design basis, one needs knowledge of the composition of the hazard calculation, including data coverage and quality, and the assumption and limitations used to define the hazard estimate. In addition, knowledge of the seismic analysis and design process is important, since it is not the level of conservatism assigned to one particular element of the process that is important, but the level of conservatism applied to the process as a whole. Thus, the definition of the design basis requires many factors to be considered. The ONR Technical Assessment Guide (TAG) 13, Annex 1, Seismic Hazards (ONR 2021) provides some guidance in this regard, stating that;

> *"…… conservatism should be introduced in a way that preferably includes consideration of the uncertainty distribution associated with the 10^{-4}/yr UHS, along with the overall robustness and rigour applied to the underlying PSHA study and its sensitivity to expert judgement"*.

On this basis TAG 13 states, with respect to defining a design basis with a suitable level of conservatism;

> *"The 84th percentile UHS provides a starting point for this consideration"*.

Whilst the 84th percentile is proffered as a starting point for consideration of an acceptable level of conservatism, it is important not to overlook the caveats in the ONR guidance, i.e. *"along with the overall robustness and rigour applied to the underlying PSHA study, and its sensitivity to expert judgement"*. This reflects the statement above, of the need for the conservatism in the design basis being applied to the 'process as a whole'.

A more prescriptive approach to defining a design basis is adopted in US guidance. ASCE 43 (ASCE 2019) and USNRC Regulatory Guide (RG) 1.208 (USNRC 2007) adopt a uniform risk spectra (URS) approach to the definition of the design basis. URS are an attempt to achieve seismic design criteria with a uniform risk of exceedance of a predefined performance objective for the structure or plant. The performance-based approach of ASCE 43 (ASCE 2019) and RG 1.208 (USNRC 2007) combines a characterisation of ground motion hazard with equipment/structure performance (fragility characteristics) to establish risk-consistent URS. The performance target (the mean annual probability of structures, systems and components (SSCs) reaching the limit state of inelastic response) results from the modification of the UHS by a design factor (DF) to obtain the performance-based URS. The design factor is intended to achieve a relatively consistent annual probability of structure/plant component failure across the range of structure/plant locations and structural frequencies. In ASCE 43 (ASCE 2019) URS are termed 'Design Response Spectra' (DRS), whilst NUREG RG 1.208 (USNRC 2007) adopts the term 'performance-based site-specific ground motion response spectra' (GMRS).

Internal consistency

From the hazard definition, through the definition of the design basis and the many elements of the design process, a wide range of disciplines, skills and individuals will be employed. It goes without saying that data, assumptions, and the level of conservatism applied, must be internally consistent throughout this process. Intuitively, the greatest risk to internal consistency occurs at the interfaces between disciplines or project phases.

Project interfaces – Information transfer

With different disciplines and experts involved at each stage of a project, the analyses and solutions discussed in one stage may not be fully understood in the next and subsequent stages of the project. Indeed, given the depth of expertise involved in some disciplines, it is a racing certainty that not all of the issues will be fully understood. The following project examples show the potential for a breakdown in the internal consistency of the data and information being passed across a project interface. These examples illustrate the importance of a project controlling mind (the Engineering Manager) to ensure internal consistency is maintained throughout the design process.

Interpretation of seismic reflection data

The development of a ground model is a key part of a seismic hazard assessment. The ground model will be developed from data and information pertaining to the regional and local geology, regional tectonics, geological structures and seismicity of the area (which may infer something about the geological structure or faults). In this respect, building a ground model is analogous to a detective solving a crime; the collection of various strands of information to build as comprehensive a picture as possible. One of the techniques used to contribute to the evidence is seismic reflection surveys, a specialist investigation technique in which the interpretation of the results lies in the domain of geophysics specialists, usually with support from geologists with specialist knowledge of the local geology. Figure 1 shows an example of a seismic reflection survey with interpreted geological structures (faults) overlain.

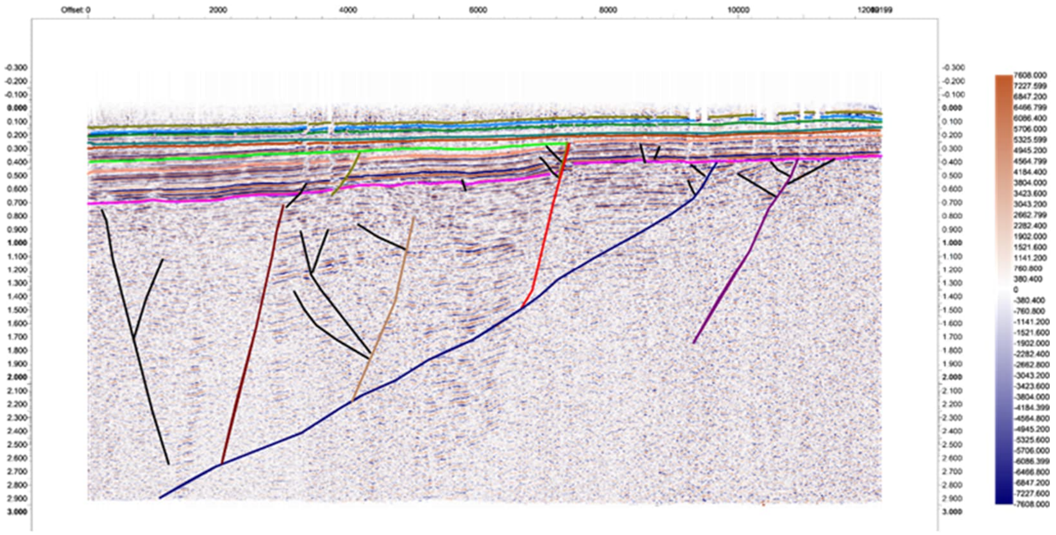

Figure 1. Example of seismic reflection survey with interpreted geological structures overlain.

The presence of geological faults can have a significant impact on the design, indeed the viability, of a nuclear facility, if it cannot be demonstrated that the faults are 'not capable' of reactivation. A capable fault is binary in terms of siting a nuclear facility; it cannot be built if it is not demonstrated that the faults are not capable (e.g. IAEA 2022). However, given the depth of specialist knowledge required to interpret the seismic reflection survey data, it is unlikely that the geophysicist or geologist making that interpretation would have a full appreciation of the implications of the decisions that they make. Similarly, it is hard to imagine that the those downstream of this process (e.g. civil and mechanical engineers) would have the knowledge to question the interpretation of the seismic reflection data. Thus, an interpretation which is inherently uncertain, is passed on to the next stage of the project as a 'tablet of stone'.

Truncation of distributions

Today, most seismic hazard assessments adopt a probabilistic seismic hazard analysis (PSHA) approach. In essence, the PSHA calculation is an integration over three variables; the magnitude (M), the distance (R) and the random variability (or uncertainty) in the ground motion level, referred to as the residual (ε). For a given ground motion parameter, the ground motion at the site is calculated for every feasible scenario (M-R-ε) and the associated frequency calculated. Summing the frequency for all possible scenarios allows a seismic hazard curve to be drawn.

When dealing with high hazard facilities, annual frequencies of exceedance (AFoE) down to 10^{-4}, and possibly lower, are required to define the design basis. For long return periods (low AFoE) the hazard estimates are driven by the tails of the Gaussian distribution of the residuals, and at

AFoE of 10^{-4}, the extreme tails of the distribution in the probability calculation become important. From a calculation perspective, the tails of the distribution need to be truncated at some point. RGP for a high hazard facility would suggest truncating the distribution at 5σ (ε=5). Truncating at a lower value could result in underestimating the hazard at long return periods.

Figure 2 (Bommer et al. 2004, Bommer 2022) illustrates the effect of truncating the distribution of ground-motion residuals by imposing different values of ε in PSHA calculations, for regions of low and high seismicity. With reference to Figure 2, for an area of low seismicity, truncating the distribution at 2σ would lead to an underestimation of peak ground acceleration (PGA) of approximately 10% at an AFoE of 10^{-4} (when compared to 5σ or 6σ). This figure would increase to approximately 22% in an area of high seismicity.

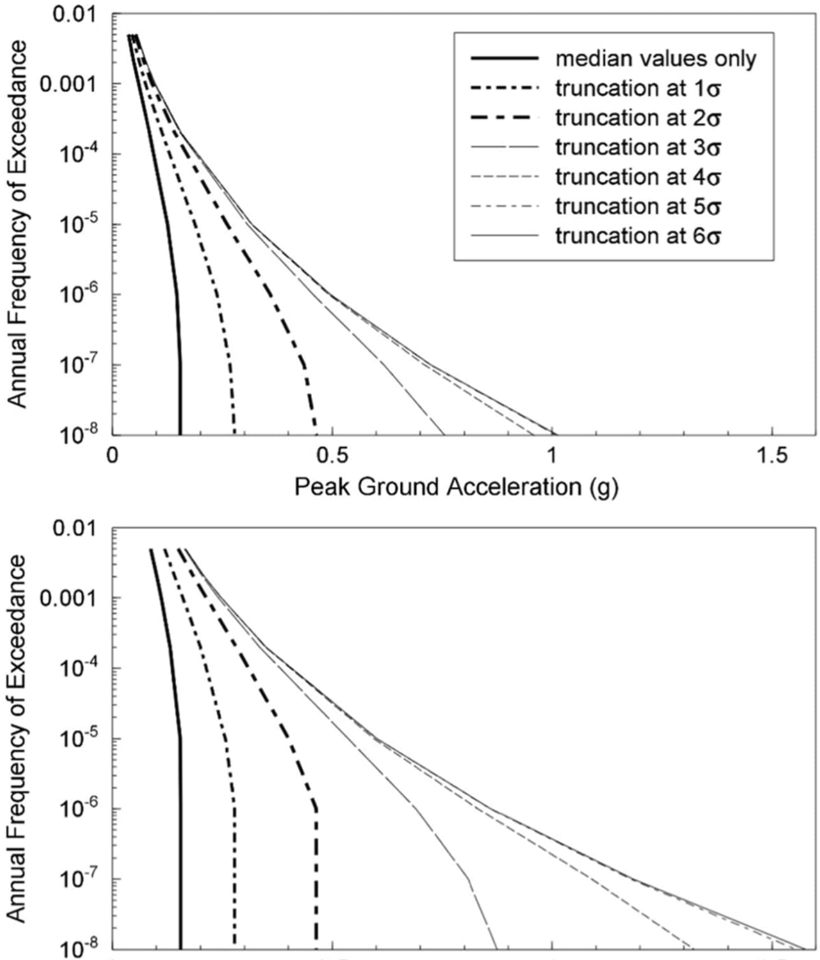

Figure 2. Illustration of the effect of truncating the distribution of ground-motion residuals by imposing different values of ε_{max} in PSHA calculations for regions of low (top) and high (bottom) seismicity rates (Bommer et al. 2004, Bommer 2022).

Definition of ground motion

It is important to understand the parameters that define the ground motion that is output from the hazard analysis and its intended use downstream in the design process. There are several definitions of ground motion in use for hazard calculations, but two common definitions used to define the horizontal ground motion are the ‘peak’ (or larger horizontal component) value and the ‘geometric mean’ value. It is these two definitions that are of relevance to a discussion of contemporary approaches to seismic hazard calculations.

Earthquake ground motions are generally recorded (and defined for design purposes) in three orthogonal directions; two horizontal and one vertical. The horizontal orientation of recording instruments is essentially arbitrary with respect to the characteristics of any earthquake that they may record (Figure 3), and it is the way in which the data from these orthogonal components are used and manipulated in hazard calculations that defines the ground motion. Some practitioners use only the larger of the two horizontal components of ground motion in hazard calculations, and ultimately to define the hazard for design purposes. This is commonly referred to as the 'peak' ground motion or 'larger horizontal component' of ground motion, and was the definition of ground motion traditionally used in seismic hazard assessments (before c2000).

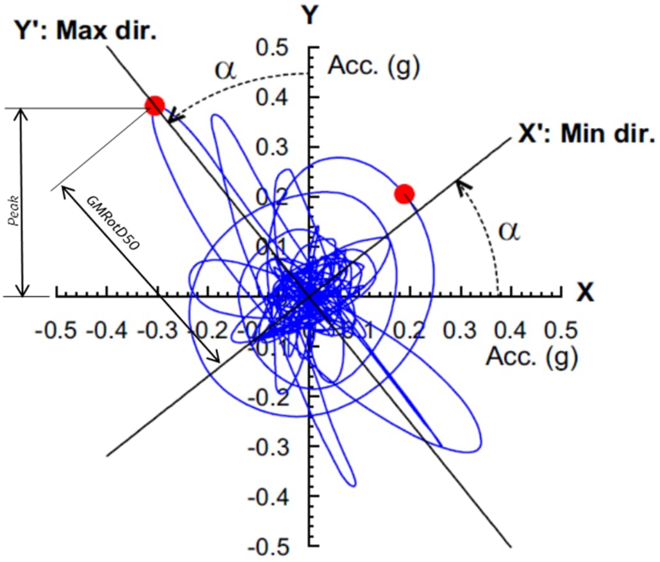

Figure 3. Definition of earthquake ground motion component (Huang et al. 2008).

In recent times, it has become common to use the geometric mean of the two horizontal components of the ground motion in seismic hazard studies. Many of the ground motion prediction equations (GMPEs) published today, adopt a geometric mean approach, therefore the resulting hazard (e.g. uniform hazard spectra (UHS)) also portray a geometric mean definition of the ground motion.

A further definition of ground motion that is occasionally used is the rotated geometric mean (GMRotD50). Pictorially, this is the maximum acceleration and its point on the orbit farthest from the origin (solid circle in the upper-left quadrant of Figure 3). This component definition accounts for the random orientation of the horizontal axis system by choosing, at each response period, the median value of the geometric mean from all possible orientations, α (Beyer and Bommer 2006). Where the maximum ordinate from all possible orientations of the horizontal axis system is used the resultant ground motion is termed 'MaxD', differing only from GMRotD50 in the fractile (100th vs 50th). The GMRotD50 ordinate is annotated on Figure 3 along with peak definition.

Traditionally, structural design codes were not specific about the definition of ground motion acceleration that they used; it was simply defined as 'acceleration' – there was no need to do otherwise, since practically all seismic hazard analyses adopted a 'peak' (largest component) definition of ground motion acceleration. Today, whilst nearly all recent ground motion prediction equations (GMPEs) use a geometric mean definition of ground motion, structural codes have generally not caught up with this subtle change and continue to refer simply to 'acceleration' with no additional changes in approach to reflect the change in the parameter. It may therefore be inferred that most design codes remain aligned to 'peak' values.

Whilst structural design codes have generally not caught up with the move towards the geometric mean definition of ground motion in PSHA studies, the developments in ASCE 7 are worthy of note. ASCE 7-16 (ASCE 2017b) defines two alternative earthquake ground motions:

- Maximum Considered Earthquake Geometric Mean (MCE_G) Peak Ground Acceleration – A geometric mean peak ground acceleration and without adjustment for targeted risk.
- Risk-Targeted Maximum Considered Earthquake (MCE_R) Ground Motion Response Acceleration – An orientation that results in the largest maximum response to horizontal ground motions and with adjustment for targeted risk. This is equivalent to the 'MaxD' ground motion, defined above.

The MCE_G peak ground acceleration (adjusted for site effects) is used for evaluation of liquefaction, lateral spreading, seismic settlements, and other soil-related issues, i.e. issues concerning the ground. The MCE_R ground motion response acceleration is used for all other situations, for example, structures above ground, which would invariably experience the maximum component of earthquake ground motion at some orientation to the structural axes.

Whilst the ratio of the ‘peak’ (larger horizontal component) motion to the geometric mean motion (GM_{xy}) is frequency dependent, it approximates to 1.1 at PGA (Beyer and Bommer 2006). If the maximum rotated component motion (MaxD) is considered, the ratio $MaxD/GM_{xy}$ approximates to 1.2 at PGA (Beyer and Bommer 2006).

Clearly, it is important to understand the measure of ground motion being used in any assessment of seismic hazard. This is particularly important when passing information from the seismic hazard assessment to those responsible for the design of structures, systems and components. Inconsistency in the definition of the ground motion may not be recognised unless this is specifically drawn to the attention of the user of the data. Left unchecked, this could ultimately result in design/assessment conclusions being drawn which are deemed to be satisfactory, but, in reality, are unconservative.

Baker and Cornell (2006) discuss the problem of inconsistency in the ground motion measure, by highlighting the differing assumptions in the seismic hazard calculation (commonly using a geometric mean value) and the structural response analysis which often uses a single horizontal component (peak value). They caution that the *“inconsistency in definitions is typically not recognised when the two assessments are combined, resulting in unconservative conclusions about the seismic risk to the structure”*.

Thus, decisions taken by the seismic hazard analyst can have significant consequences for the structural analyst/designer if the basis of their assessment is not clearly communicated. Consider the two issues outlined above; truncation of the distribution of the residuals and the selection of the geometric mean ground motion. If the seismic hazard analyst truncated the residuals distribution at 2σ and adopted a geometric mean ground motion definition (as opposed to peak), the ground motion passed to the structural designer could be of the order of 20% below that defined by the design code (1.1 x 1.1 = 1.21).

The ground motion definitions of geometric mean and peak are largely the preserve of those involved in seismic hazard analysis. Few civil or structural engineers will have any notion of these definitions, (mechanical and electrical engineers even less so). Thus, if the definition of ground motion and its relation to the ‘acceleration’ defined in the design codes is not clearly spelt out, along with any limitations of the seismic hazard calculation (e.g. truncation of distributions), then there is high probability that incorrect, potentially unconservative, ground motion parameters are taken forward into the design process.

Analysis models

In developing any geotechnical or structural design, a ‘model’ of some description will be required, whether it be a simple beam or stick model, or a complex three-dimensional finite element model. Anecdotally, it would appear that the latter is becoming more commonplace, probably reflecting the increasing accessibility of low-cost computing power, rather than engineering justification.

Of course, all analysis models are just that - ‘models’. They are only as good as the assumptions and limitations of their construct. The oft-quoted aphorism that *“all models are wrong, but some are useful”* (Box 1976, Box and Luceño 1997), is worthy of consideration when developing models for seismic analysis.

“Since all models are wrong the scientist cannot obtain a ‘correct’ one by excessive elaboration. …… Just as the ability to devise simple but evocative models is the signature of the great scientist so overelaboration and overparameterization is often the mark of mediocrity” (Box 1976). In other words, the mark of a good model does not lie in complexity, but in defining an economical description of the natural phenomena under consideration. Just as with other aspects of design and construction, in terms of analysis models, it is important to know what matters and what does not – *“It is inappropriate to be concerned about mice when there are tigers abroad”* (Box 1976).

Where a structure or system exhibits non-linear behaviour, it may be necessary to resort to time-domain numerical modelling to fully understand the response under seismic loading. For example, where it is necessary to analyse ground-structure interaction; soils are non-linear, history dependent, two-phase materials, which cannot be adequately described using simple elastic models. Time-domain analysis is also used where there is a requirement to generate secondary response spectra (SRS) for the design of secondary systems, e.g. mechanical and electrical plant.

In recent years there has been an increasing trend towards complex three-dimensional, non-linear models, perhaps reflecting the development of powerful computers and software. However, where SRS are required, perhaps of more importance, is the ability to capture the high frequency response which may be critical for the design of the secondary systems. In this respect, the numerical integration scheme and the model boundary conditions may be more important than the details of the model itself.

Whilst establishing an appropriate location for model boundaries may be a fairly obvious criterion to ensure a stable model (usually checked by validation studies), the importance of the type of boundary is, perhaps, less obvious.

The dynamic input can be applied at the lower boundary of the model in a variety of ways; as an acceleration history, a velocity history, a stress history or a force history. The application of acceleration and velocity histories to the lower (fixed) boundary effectively constrain the boundary to move with the input motion. The boundary is consequently a reflective boundary - any waves incident to the boundary will be reflected without loss of energy. When this approach is adopted, a seismic motion is input into the model and travels through the model, and, depending on the material properties assigned to particular parts and the impedance contrasts within the model, will be partly damped, but crucially reflected elsewhere within the model. Thus far, that represents a reasonable representation of reality. However, when these reflected waves reach the fixed base of the model, they are reflected once again, back into the model – a standing wave is created, which is not representative of reality. In essence, energy is ‘trapped’ within the model.

As an alternative, a viscous (or absorbing) boundary can be specified, which is the equivalent of having tuned dashpots in the normal and shear direction (Lysmer and Kuhlemeyer 1969). With this approach, waves incident to the boundary from inside the model are absorbed and not reflected back into the model. Absorbing boundaries cannot be used in conjunction with applied acceleration or velocity histories. Therefore, the dynamic input has to be applied by using a stress or force history at the absorbing boundary.

Figure 4 shows a two-dimensional (plane strain) model of a dry dock. The different colours indicate different material densities and distinguish the concrete dock structures from the surrounding soil and bedrock. The line elements represent structural members (e.g. piles) or superimposed structures, (e.g. dockside crane).

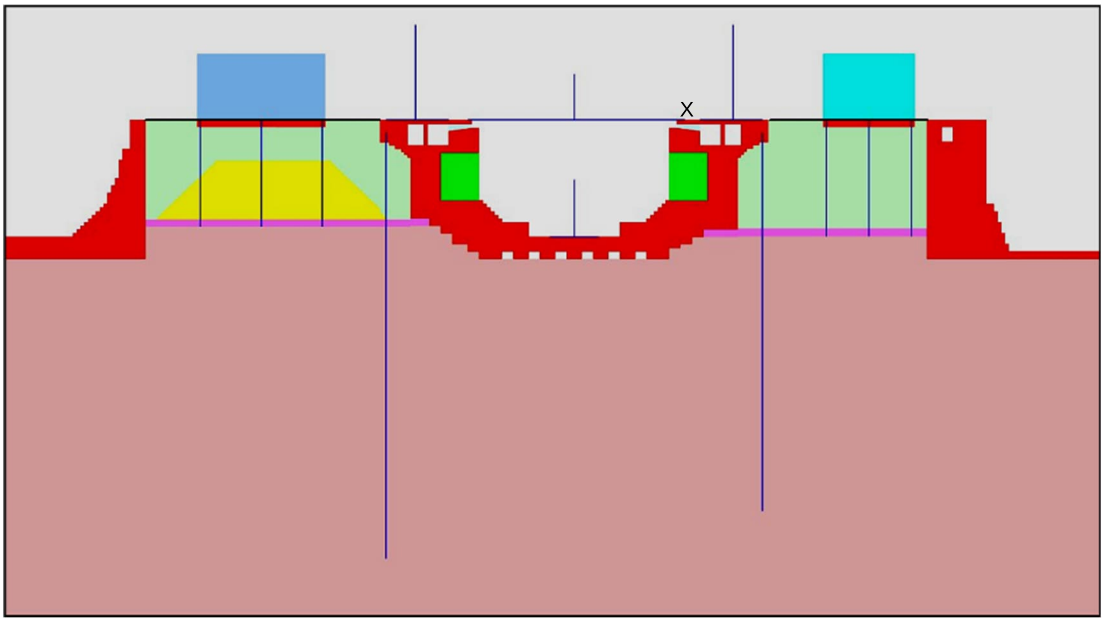

Figure 4. Plane strain model of drydock and associated structures and plant.

Figure 5 shows horizontal secondary response spectra recorded at the cope edge of the dock wall (marked ‘X’ in Figure 4). Two examples are illustrated; the SRS derived from a reflecting boundary model and that from an absorbing boundary model. It is clear that a significant difference in response is recorded above about 6Hz. This represents the effects of trapped energy in the model, which could have a significant impact on the design – and cost – of mechanical and electrical plant located on the dockside, which may be susceptible to those higher frequencies. Thus, judicious selection of not only the location of model boundaries, but also the type of boundary, can have a significant bearing on the model performance and results. In this case, inappropriate selection of model boundaries by the civil engineer building the model, could pass-on significant over-conservatism to the mechanical and electrical engineers designing dockside plant and equipment.

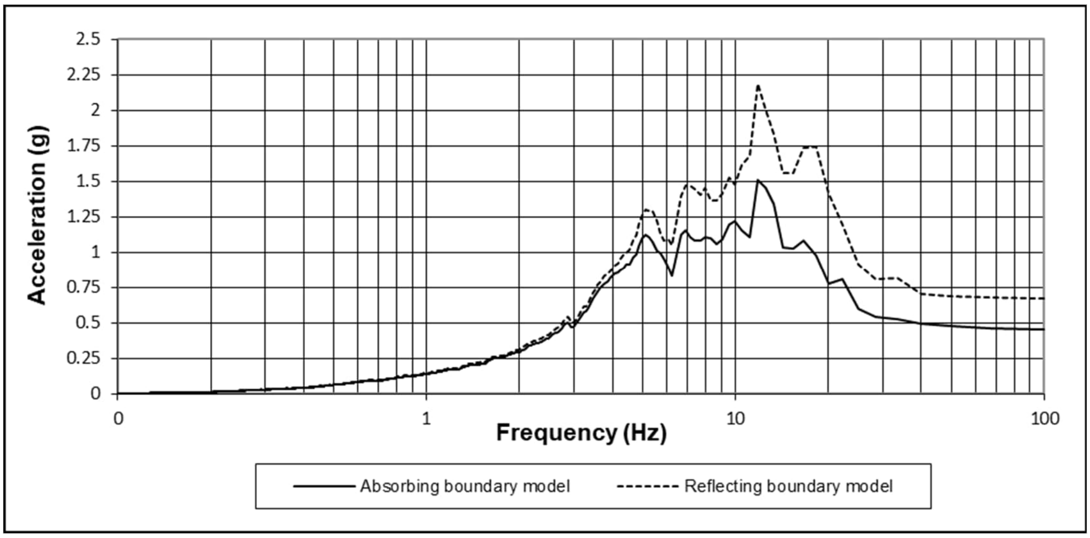

Figure 5. Effect of absorbing boundaries – cope level horizontal SRS.

Design of secondary systems

In building structures, it is common practice for building services to treated as ‘secondary systems’ in terms of seismic design. To do otherwise, would have significant consequences for analysis models due to the significant differences in terms of mass and stiffness from the building structure.

A secondary system is one in which the response of the (secondary) system does not significantly influence the response of the primary system (i.e. the building onto which the secondary system is attached). Guidance is presented in ASCE 4 (ASCE 2017a) on the criteria for assessing the need for a coupled analysis, or otherwise. Generally, if a coupled analysis will not increase the response of key design parameters of the primary system over that of a decoupled analysis by more than 10%, then a coupled analysis is not required (ASCE 2017a). Fortunately, an error in calculating the coupled modal frequency will generally be conservative (Hadjian and Ellison 1986).

Secondary response spectra can be generated at any point within the building, which can then be used in a separate modelling exercise to design the secondary system. Such an approach is typically used for the design of building services, including pipework and cable trays.

The analysis of building structures and the generation of secondary response spectra is usually conducted by civil/structural engineers, whilst the design of mechanical and electrical systems is usually carried out by mechanical and electrical engineers, respectively. The transfer of the information from one to the other is akin to a ball being thrown over a wall; the structural engineer produces the secondary response spectra; the mechanical and electrical engineers design their systems, usually without too much thought being given to the impact of their respective systems on the primary structure. The photographs in Figure 6 show electrical cable trays carrying a significant weight of cable beyond that assumed in design - a secondary system with notional load.

Figure 6. Examples of heavily loaded cable trays designed as secondary systems.

In both of these examples, the lack of appreciation between the disciplines of each other's work is clear. The structural engineer passes over SRS without too much thought of the mass and stiffness of the cables that will be supported off the structure, and the electrical engineer has no awareness of the potential implications of such large cable bundles on the structural behaviour.

What really matters

What is driving the solution

Whilst the design of most structures invariably follows a set, logical pattern, e.g. defining the geometry and loading condition, conducting analysis to determine forces and displacements, code compliance checks etc, it is important that this process is not allowed to commence without first understanding what the key issues are for the design. Some things matter more than others and have a greater influence on the outcome. Just as there are some variables which have a significant influence on the hazard, so too, there are some issues which have a significant influence on the design and performance of the structural solution, i.e. they are 'design significant issues', which will influence, and may even dominate, the design process.

Ground conditions, site constraints, or user requirements can all influence the design solution. It is important to understand what is driving the design, what are the constraints and what is the required outcome? Prior to the commencement of the design process, or at least in the early stages of design, the Engineering Manager (the controlling mind) needs to know the answer to these questions, so that an efficient design process is followed, and time is not expended needlessly pursuing a design solution that will not match expectations or worse still, developing a solution that has ultimately no hope of achieving the objectives. The following project examples illustrate situations where one issue dominates, and drives, the analysis/design solution.

Cooling water intakes

Occasionally the design solution is driven not by design variables, but by the construction methodology. For example, Figure 7 shows a cooling water intake structure for a nuclear power plant, which is located on the seabed, offshore of the power station, and is connected to the power station by a shaft and tunnel system. Clearly the hydraulic engineering design of this structure is important, but so too is the performance during and after a seismic event, as failure of any part of the cooling water system during a seismic event would compromise the safety of the plant.

There are four of these structures serving the nuclear power plant, in addition to two smaller outfall structures. Each of these structures is approximately 44m x 17m x 8m and weighs approximately 4750 tonnes. They are installed from barges using large floating cranes (Figure 7). Given the cost and programme implications of installing such large structures offshore, it is imperative to minimise the time spent for this operation. Thus, the design is driven by construction requirements and practicalities of placing these structures on the seabed. This includes construction tolerances for excavation and preparation of the seabed in a very high tidal range (13m) with high currents, as well as the more obvious issues of dimensions, weight and transportation of the units.

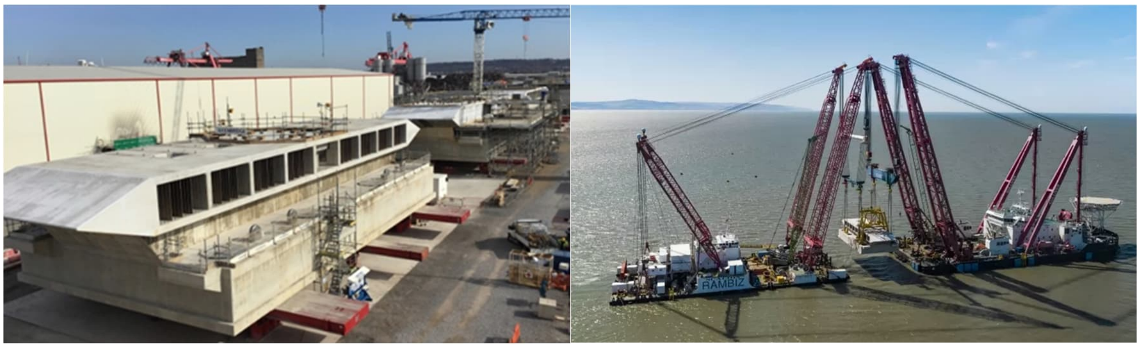

Figure 7. Construction of cooling water intakes for a nuclear power plant. (Photographs courtesy of EDF NNB GenCo).

From a seismic design perspective, it was particularly desirable to avoid the need for a physical connection to the seabed (e.g. piles), thus avoiding the inevitable construction complications and the time and cost for installation. Thus, the focus of the design became developing and substantiating a solution whereby the intake/outfall structures could sit on a prepared surface on the seabed, without the need for piles, a solution that was subsequently achieved. In this respect, the construction methodology eclipsed any 'normal' analysis or design refinement that one might initially think was appropriate. In other words, the design was driven by the construction methodology, rather than any loading condition or material constraint.

Water tank

All design codes have inherent assumptions around construction tolerances, build quality, loading tolerance etc. Occasionally, a situation arises where the completed structure does not comply with those inherent assumptions, in which case, the structure is 'non-code compliant'. Figure 8(a) shows a graphical representation of a large cylindrical water tank (1.4 million litres capacity), which had to remain fully functional following a 10^{-4} (AFoE) seismic event. The tank is of stainless steel construction and was assembled insitu, by welding pre-shaped plates together. Due to poor control of the welding process, the tank deformed in excess of code tolerances. Whilst localised areas being out of tolerance would be unlikely to be problematical, in one area the cumulative effect of the weld distortion resulted in noticeable deformation in the tank wall, leading to concerns over whether or not premature buckling of the tank wall could result during a seismic event. Thus, an accurate representation of the geometry of the structure now becomes particularly important in determining the withstand capacity of the tank; it becomes 'the thing that matters'.

In this particular case, an accurate representation of the geometry was achieved using a 3D laser scan of the tank (Figure 8(b)), which provided a surface resolution of 13mm (between data points) with an accuracy of 0.01mm for each data point. Having established an accurate geometry of the tank, an analysis could be conducted to determine the response under static and dynamic loading. Various analyses were conducted, including the modelling of both non-linear geometric and non-linear material effects, allowing an accurate simulation of the failure mode as the load was continuously increased. Therefore, it could be determined if local stress concentrations were related to the ultimate failure mode of the tank. The results of the analysis showed that the small areas of stress concentration due to the weld distortion were not significant in terms of tank load carrying capacity and would not induce buckling.

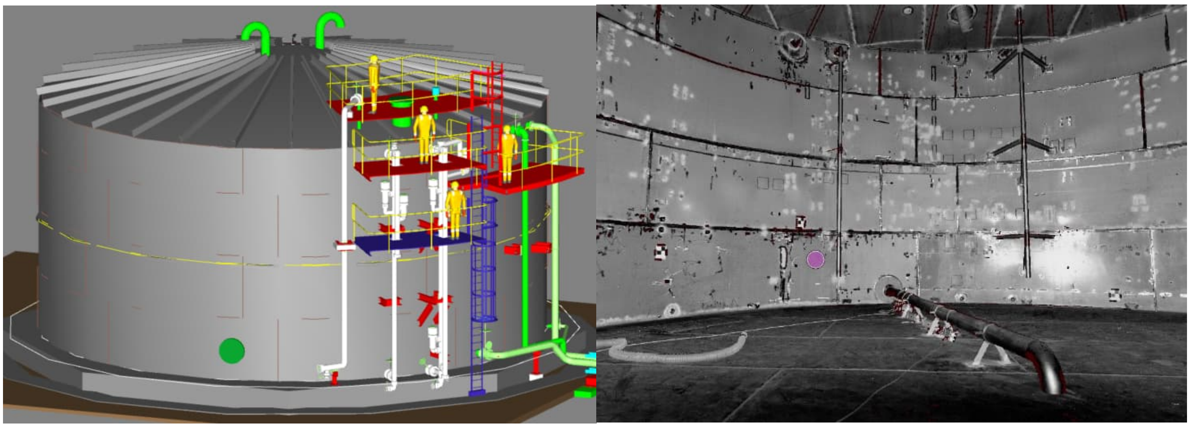

Figure 8. Cylindrical water tank; (a) graphical representation, (b) Internal laser scan.

Skills of a controlling mind

Consulting engineering has become increasingly divided into specialisms and, as a consequence, has become more siloed. This can possibly be attributed to the fact that there has been considerable consolidation in the industry; we have moved from many small to medium sized consulting engineering firms to a small number of large firms dominating the market. This, inevitably, has spawned the clustering of engineers into specialisms in the name of efficiency, and further subdivided into market-facing groups, again, supposedly in the interests of efficiency and optimisation of the service/delivery model. Whilst some of these benefits may have been achieved, it comes at the expense of limiting the breadth of experience that engineers are exposed to. Despite being a specialism in its own right, seismic engineering has not escaped this organisational change, with many sub-specialisms developing within the broad field of seismic engineering. Of course, clients have a reasonable expectation that any project will be delivered in a way that is seamless and internally consistent from concept to completion, but paradoxically, the consequence of these organisational changes, and the potential absence of a controlling mind, means that this expectation may not be realised.

An Engineering Manager on a project, needs to understand enough detail of the specialisms to be able to understand, and influence, the assumptions, the limitations and the uncertainties at each stage, so that they can fulfil the role of the project controlling mind. As the controlling mind, the Engineering Manager needs to understand the issues that drive the design process and be able to manage the various disciplines and specialisms, such that the transfer of data and design information is appropriate, unambiguous and internally consistent.

Clearly, one cannot attain a detailed, expert, knowledge of all disciplines or specialisms. However, if one is to be the controlling mind, one needs to have a broad understanding of all aspects of the work, with sufficient depth of knowledge of each aspect to be able to understand, challenge and direct the work. Realistically, this breadth and depth of knowledge can only be gained over a period of time, with exposure to a variety of roles across a variety of projects. However, this does not mean that such a goal is unattainable. A young engineer with an interest in seismic engineering and a desire to seek out challenging and diverse roles from one project to the next, will progressively and methodically develop the breadth and depth of knowledge required to fulfil the role of the controlling mind.

Given the rise of specialisms within industry, there is perhaps a greater need than ever to develop young engineers to be ‘generalists’, who have the breadth and depth of experience to fulfil the Engineering Manager role and be the controlling mind across the design process. That industry has this clear need, should provide a great incentive for any young engineer proactively to seek out such opportunities and develop their career accordingly. Seismic engineering is a fascinating and rewarding area in which to work, and there are many opportunities in industry for those willing to grasp them.

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